GOES I-M On-Orbit Storage Mode and Operations Plan

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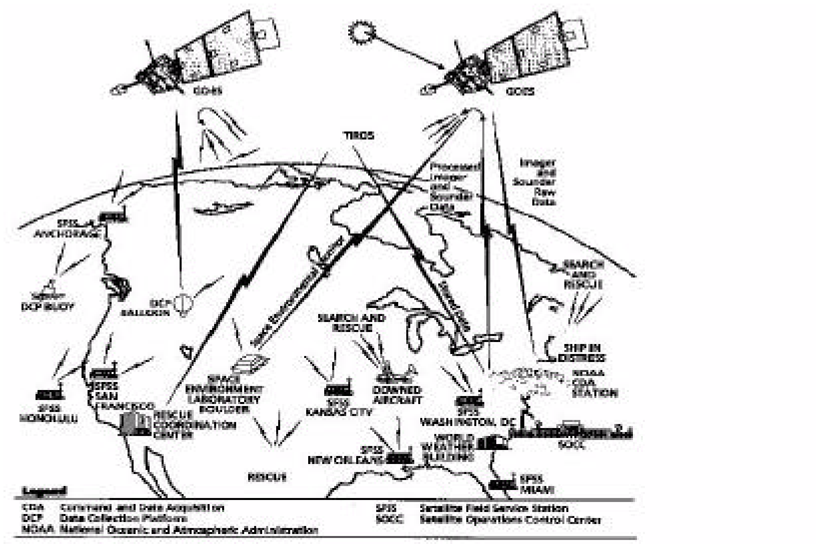
ABSTRACT

The compression of the GOES-K launch schedule from 1999 to March 1997 stimulated the formation of ideas for managing three operational spacecraft with available ground resources for two operational spacecraft. On-orbit storage of one of these spacecraft supplemented with automated ground system monitoring enhancements, was determined to be the best possible option for relieving the strain on the limited ground system support capabilities. This paper discusses a viable mode of storage for a GOES I/M satellite that minimizes use of ground resources, preserves spacecraft equipment lifetime, and provides a stable attitude and thermal environment. A strategy that uses a spin-stabilized attitude about the principal axis, with a minimal equipment configuration is outlined. This stable mode requires a minimum amount of monitoring and infrequent spin-axis adjustments to maintain precession for Sun tracking, and it eliminates the need for use of several life-limited components, including the Imager, Sounder (including filter wheel), momentum wheels, and Earth sensors. In this spin-stabilized mode, the GOES spacecraft mass properties add additional complexity due to the degeneracy in Ixx and Izz. Results are provided on the flexible body analysis for the primary appendages (solar sail and array) and fuel motion, and the resulting change in the principal axis due to energy dissipation. A technique is proposed for performing periodic spin-axis adjustments using flight software capabilities to allow simultaneous thruster firings to provide a torque about the principal axis. The consequences on the spacecraft power budget and thermal environment are also considered. Finally, automation of operations and future applications of ZAP Storage are addressed.

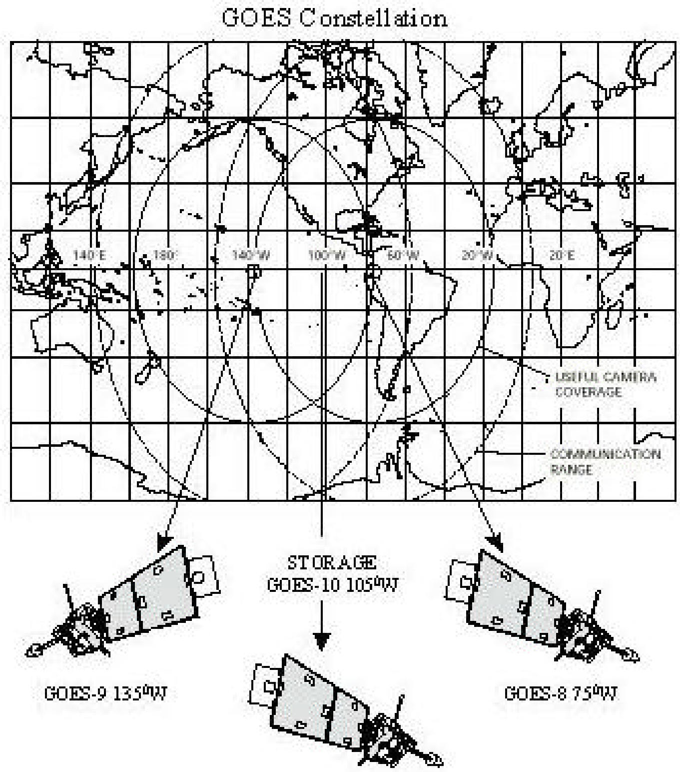
INTRODUCTION

Acting as the technical acquisition experts for the National Oceanic and Atmospheric Administration (NOAA), NASA has responsibility for designing, developing, testing, launching and delivering on-orbit, operational spacecraft systems dedicated to state-of-the-art weather product generation for the United States. This relationship began in December 1966 when NASA launched the first Applications Technology Satellite (ATS-1), giving NOAA's National Weather Service (NWS) the ability to view weather systems imaged on a global scale for the first time. Operational use of ATS full disk imagery at the National Severe Storm Forecast Center (NSSFC) and the National Hurricane Center (NHC) became a mainstay of forecasting. From this early beginning, incremental improvements have been made in the observatories, but the GOES 4-7 series spin-stabilized spacecraft could not simultaneously conduct imaging and sounding as the spinning VAS instrument (Visible and Infrared Spin Scan Radiometer [VISSR] and Atmospheric Sounder) viewed the earth only 5% of the time. NASA contracted for GOES I-M in 1985 (to become GOES 8 and above), and with it came the advent of dramatically increased observation capabilities. This three-axis stabilized spacecraft bus allowed, for the first time, continuous imaging and sounding from two independent and dedicated instruments. This provided the NWS with their first opportunity to receive continuous high quality, high resolution sounding and imaging data—truly GOES Next generation. The fact that this spacecraft was constantly “staring” at the earth also provided expanded flexibility, allowing for custom scan scenarios for specific regional or event-driven data collection (Rapid and Super Rapid Scan). Secondary instrumentation was also improved, with Space Environmental Monitoring instrumentation, improved Data Collection Platform instrumentation, Search and Rescue receiver, and a new data format for retransmission of raw Imager/Sounder data to direct-receive users (termed GOES Variable Format (GVAR)). With these dramatic improvements, GOES data quickly became an even more critical part of NWS operations, providing day and night information about existing and emerging storm systems across the hemisphere.

This dramatic increase in capabilities came with an equally significant increase in data rates, data formatting requirements, precise control of bus pointing, image/sounding data generation and earth location, and demanding significantly more complex commanding requirements (in excess of 5000 commands per day, per spacecraft compared to the 1-200 commands per day for GOES-7). As a result, a new ground system was developed and increased staffing was necessary to operate the system, which consists of a 2 satellite constellation. The new ground system supports two major functions: (1) spacecraft and instrument health and safety monitoring, commanding, and operations analysis, and (2) Imager and Sounder instrument data processing. For each operational spacecraft in the constellation, the ground system also provides synchronous orbit and attitude determination to support Image Navigation and Registration (INR), and orbit predictions, maneuver planning and commanding, and telemetry processing and analysis to support daily and periodic satellite operations. Ground system requirements for stored spacecraft only eliminates the need for raw instrument data processing, GVAR and INR (after post launch testing was complete). Significant staff and ground system resources for orbit predicts, system monitoring and commanding would still be required to store these 3-axis stabilized spacecraft, resulting in high recurring costs, and loss of ground system redundancy for operational spacecraft—unacceptable alternatives for NOAA.



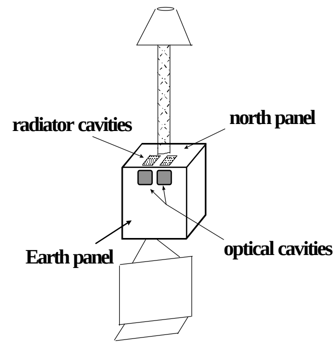
Despite the successes of the GOES program to-date and well programmed improvements, problems plagued GOES I-M development and production in the late 1980s and early '90s. After loss of GOES-G at launch (to become GOES-7), GOES-H (now GOES-7) was launched and became the sole operational spacecraft while GOES-I (to become GOES-8) was still in the production cycle. GOES-7 alone on-orbit for nearly 3 years created a single-satellite constellation, resulting in reduced NWS model accuracy and even contributing to socio-economic losses from an inability to simultaneously cover severe weather events and provide appropriate early warnings across all 50 states (20^0W to 180^0W). The charter of NASA and NOAA Operations became re-establishment and maintenance of a 2-observatory constellation, with rapid replacement capability having become a critical factor. GOES-8 was launched in April 1994, and GOES-9 in May 1995. With the 2-spacecraft constellation re-established, NASA's efforts turned to developing a method of ensuring 2-satellite coverage by minimizing the time-lag between operational spacecraft failure, and replacement. GOES launches are executed primarily as commercial launches, therefore an expedient launch could not be depended upon as an immediate call-up option. Additionally, indefinite storage of a spacecraft on the ground dictates post-storage testing based on storage period, to revalidate functionality and performance prior to launch. These 2 constraints yielded a somewhat unpredictable call-up-to-launch interval that could leave the NOAA/NWS with single satellite coverage for up to 18 months—an unacceptable alternative. Therefore on-orbit storage was determined to be the most viable option to support rapid replacement on-orbit. NASA Operations undertook an ambitious task to develop, test and implement a storage configuration and technique in only 12 months—from GOES-9 handover to NOAA to the beginning of GOES-10 pre-launch preparation activities. Significant challenges in accomplishing this included technical obstacles and program policy re-direction. Technical hurdles included such issues as Electrical/Electronic/ Electromechanical (EEE) part radiation survivability for an additional 2 years in-orbit, mechanical systems reliability with an additional 2 years of operations, maintaining thermal balances with equipment that was never intended to be un-powered for significant time periods, and solar intrusion control for sensitive instrument telescope assemblies. Programmatic challenges included convincing NOAA management that on-orbit storage was viable and should again become program policy after it was abandoned prior to GOES-8, eliminating the impact to NOAA ground systems and redundancy for operating the 2-satellite constellation while storing a third, and not increasing the operations staff to operate a stored satellite. Imaginative approaches, extensive studies and analyses, and repeated simulations and fine-tuning culminated in launch of GOES-K (becoming GOES-10) on 25 April 1997 to 105^0 West for on-orbit test and storage.



STORAGE MODE DESCRIPTION

A significant advantage of on-orbit storage vs. ground storage is the elimination of lead time for ground storage callup and preparation and the scheduling of launch services. On-orbit storage dramatically reduces this lead time from months or years down to days or a few weeks that are needed to recover normal pointing control and re-validate key flight hardware not used during on-orbit storage before starting operational imaging.

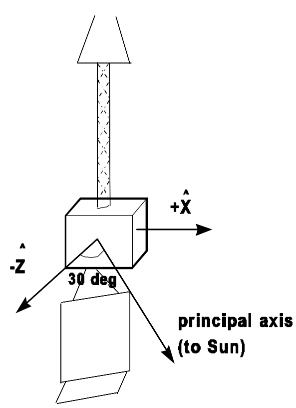
The Z-Axis Precession (ZAP) on-orbit storage mode minimizes risks to spacecraft health and safety while at the same time preserves as much as possible the full operational lifetime capabilities of flight equipment. In ZAP mode, all operational thermal constraints were adhered to by designing a storage configuration that maintained sufficient power and heater operations. This included adding 2 additional 23 Watt heaters to the mounting panel interface between the spacecraft bus and the Imager/Sounder baseplates in order to provide a supplemental heat source to their respective 60 Watt baseplate heaters. In addition, care was taken during ZAP mode design to avoid known storage mode attitudes that cause potential overheating of the Imager and Sounder due to direct sunlight. The ZAP mode attitude constraints keep the Sun well away from the optical ports on the Earth face and at least 66.5☜ away from the instrument radiators on the north face where it could cause potential damage to the internal optics or degrade instrument patch performance.

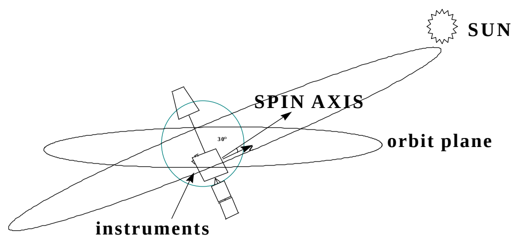


ZAP mode design also minimizes wear on mechanical components and use of fuel by eliminating their need during storage mode. Critical life-limited equipment (such as momentum wheels, stepper motors, and instrument servo motors) are not used in ZAP mode, preserving their parts and lubricants from continuous wear and degradation. The passive control used in ZAP mode significantly limits the propellant use to that required for ZAP spin maintenance, and activation/de-activation maneuvers. Further fuel savings is made through optimization of the ZAP orbit and maneuver sequences.

The ZAP orbit and attitude orientations are designed to meet these requirements. The ZAP orbit was selected to minimize or eliminate the need for stationkeeping maneuvers. With an initial inclination of 0.5☜ and a subsatellite longitude at the stable geopotential location at 105☜ West, the long term ZAP orbit drift is maintained within acceptable limits without any stationkeeping maneuvers.

The ZAP attitude orientation has the spin axis aligned along the spacecraft principal axis, which is maintained in the direction of the Sun and normal to the solar array which is stationary during steady-state ZAP. The principal axis position is in the spacecraft XZ-plane, 30☜ from the -Z axis (anti-Earth face) in the direction of the +X axis (East face). In this orientation, the instruments are always pointing away from the Sun, eliminating any concern over sun exposure in the optical cavities. The amount of sun exposure to the radiator cavities, however, is dependent upon an understanding of the ZAP dynamics; precise knowledge of the spacecraft inertial properties; and the ability to manage spin axis drift away from the Sun. The bulk of the ZAP design analysis was focused on understanding and planning for these issues.





Rigid body dynamic simulations were performed during the ZAP design phase in order to characterize the environmental torques on the spacecraft. At geosynchronous orbit, solar radiation pressure and magnetic torques are significant. High-fidelity simulation models, modified to reflect in-flight measurements for GOES-8 and GOES-9, were developed to perform this analysis. Incorporated in the dynamics simulation was a constant spacecraft dipole, provided by magnetic torquers that injected a constant torque in the ecliptic plane used to precess the spacecraft with the Sun. These simulations re-inforced the confidence that, assuming the solar array is precisely oriented normal to the principal axis, the spin axis drift is manageable over a conformable duration of 2-3 months before the Sun cone in the spacecraft body exceeds the 23.5° limitation with respect to the instrument radiator cavity on the north panel.

Predictions of the principal moments of inertia are normally provided by the spacecraft manufacturer for various stages of the mission. In order for ZAP to be successful, knowledge of the precise location of the principal axis at the time of ZAP activation was required. An iterative plan was implemented for determining this information. In this plan, the nominal ZAP activation MOI was predicted based upon pre-launch analysis and planning. Based on dynamics analysis using this information, the nominal solar array position was determined. ZAP was initiated using these nominal settings. Using integrated gyro rates collected for several days, the offset of the true principal axis from the predicted can be empirically derived. A followup adjustment of the ZAP activation sequence and the ZAP solar array position is performed to correct for the difference.

The ZAP activation sequence takes advantage of control system features to provide a single-axis impulse about the principal axis with the desired spin rate, thus minimizing the initial cone angle and nutation damping period. The impulse is provided by open loop thruster firing combined with a feed-forward commanded torque that produces simultaneous thruster firings about three axes, with a net impulse torque about the desired Euler axis. Tight inertial control to maintain pointing at the time of the thruster firing took advantage of an unused control mode known as Perigee Velocity Augmentation (PVA), that was originally expected to be used when GOES was planned to be deployed by the space shuttle. The torque biases that are applied are a natural feature of the on-board stationkeeping flight software, and are designed to be used as a constant feed-forward torque command utilized during translation maneuvers. Prior to ZAP mode, the torque pre-bias and PVA features were never used in-flight. The ZAP activation sequence timing is driven by several factors including: T&C antenna coverage; solar intrusion avoidance into the instrument optics; and minimization of battery usage during spacecraft slews that oriented the spacecraft for ZAP and moved the sun off of the solar array.

ZAP maintenance maneuvers are performed when the drift of the spin axis away from the Sun causes the Sun coning angle relative to the spacecraft body to reach 20° (3.5° below the instrument radiator cavity solar constraint). The maneuvers are performed using proven transfer orbit acquisition modes and sequences that are optimized to ensure continuous T&C coverage;

minimum propellant use; and minimum overall time for equipment usage (such as gyros). The maneuvers re-align the principal axis at the Sun and exercise the same thruster firing sequence used for ZAP activation. Using this technique, 5-6 ZAP spin axis maintenance maneuvers are expected to be performed every year, using a yearly total 12 hours (out of 2000) of gyro lifetime and 1.0 kg. (out of approximately 190 kg.) of propellant.

ZAP de-activation occurs at the time of callup, when one of the 2 operational GOES spacecraft is classified as inoperable. The ZAP de-activation maneuver sequence employs the same techniques used for initial on-orbit Earth-pointing at the end of transfer orbit. Thruster control modes are used to acquire coarse Earth pointing. After momentum wheel spinup, spacecraft attitude determination allows for a yaw momentum alignment relative to orbit normal, providing a fine tuning for wheel control transition. The first few days after return to normal operations are dedicated to optimizing yaw momentum, initializing instruments, and verifying spacecraft equipment functionality. About one week additional time is required for INR startup. Consequently, the spacecraft is ready for operational imaging at the storage position within 2 weeks after callup from storage. Operational imaging continues as the spacecraft is moved to its new longitude as an on-station replacement.

Eclipse season (approximately 45 days centered about each equinox) is another period of special ZAP operations. These operations consist of shedding sufficient spacecraft loads (primarily heaters) to stay within the battery DoD budget of 60% while at the same time maintaining all mission thermal constraints. During each eclipse day, these loads are shed immediately before the start of eclipse and re-established as soon as sufficient solar array power returns at the end of eclipse.

To complement the spacecraft operations plans for ZAP mode, ground system procedures and enhancements have been developed with the goal of making ZAP operations as simple as possible. In order to be comparable to ground storage that requires no manual ground intervention or monitoring, ZAP ground operations are simple, requiring little or no additional work on the part of the daily operations staff. The ZAP mode ground system resources plan has the feature that no commanding is needed during steady state ZAP operations. This plan utilizes built-in autonomous ground system resources such as a set of ‘intelligent’ pseudo-telemetry specially designed to provide a simple state of ZAP health & safety for the operator that supplement the normal spacecraft telemetry stream; RF monitoring information that autonomously verifies T&C carrier lock (without requiring a command uplink) as the spacecraft T&C antenna moves in the solar-inertial orientation; and contingency procedures that are simple to follow that assist the operations staff in identifying and quickly recovering from a ZAP mode anomaly. These contingency procedures are built so that they can be easily automated as part of future ground system enhancements.

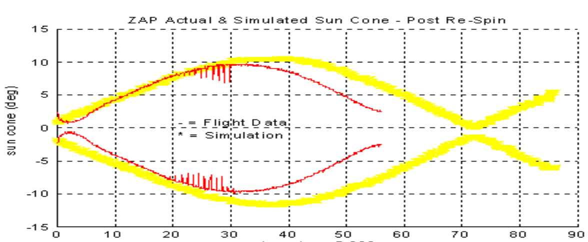
FLIGHT EXPERIENCE

ZAP mode was initially tested in-flight for the GOES-10 mission from 4 November 1997 to 13 January 1998. One spin maintenance maneuver was performed on 22 November 1997 as a result of refinements to the location of the principal axis that were empirically derived after the 4 November ZAP activation. The ZAP activation sequence on 4 November 1997 was nominal and followed the expected sequence of events with one major modification. As a result of a GOES-10 solar array anomaly on 26 May (see ‘GOES-10 Solar Array Drive Anomaly and Analysis’, M.

Phenneger et al), the solar array was limited to motion in only one direction (reverse). Consequently, all solar array slews in the ZAP activation sequence were modified to comply with this restriction. This modification resulted in an unexpected temperature rise (to near operational limits) for the X-Ray Positioner (XRP) electronics module, which was exposed to the Sun when the Sun was incident on the back of the solar array. Otherwise, all spacecraft equipment and control system performance during the activation sequence was as expected. The thruster impulse to initiate the spin resulted in a 7.5° coning angle about the sunline. Following the activation sequence, integrated gyro data was collected to determine the true position of the principal axis. The results of the gyro rate data analysis indicated a 5° error in the direction of the +X-axis.

A subsequent spin adjustment maneuver was planned and executed on 22 November 1997. This operation proceeded as nominally planned. This time, the open loop thruster firings and torque prebiases were adjusted to provide the torque about the new principal axis location. This sequence was executed as planned, resulting in a coning angle of 2° about the sunline. However, due to the solar array anomaly slew direction constraints, the solar array was not re-aligned to true principal axis normal. As will be shown, this affected the subsequent steady-state ZAP dynamics.

Steady state ZAP mode operations continued from 22 November 1997 through 13 January 1998, at which time GOES-10 was returned to normal mode operations for resumption of post launch testing. All spacecraft operations were nominal during these steady state operations. All component temperatures were well within expected ZAP limits, confirming pre-ZAP thermal analysis. Average power consumption was 93% of normal on-orbit power, primarily due to the additional heater power required to maintain acceptable temperatures. Most important was the validation of the spacecraft dynamics during steady state ZAP. This drift is a function of the strength of the solar radiation torque and the magnetic dipole torque applied to precess the spin axis with the Sun. The figure below illustrates the true vs. Predicted spin axis drift during the period of steady state ZAP mode. Note that the true drift of the spin axis almost exactly matches the prediction for about 30 days, but diverges for the final 15 days. This divergence is primarily due to the fact that, during the spin adjust maneuver, the solar array was not re-aligned normal to the true principal axis. Consequently, the solar radiation torque altered the spin axis drift, albeit in a beneficial direction (i.e., away from the 20° constraint).



SUMMARY/CONCLUSIONS

The ZAP mode of storage has been an exceptionally successful example of fine tuning operations and capitalizing on spacecraft capabilities to produce a new mode of operations. The result has provided an extremely rapid on-orbit spacecraft replacement capability that ensures 2-satellite coverage for weather forecasting and warning, ensures maintenance of spacecraft and constellation reliability through effective preservation of life-limited spacecraft resources, and minimizes operational impact to the operations organization through operations simplification and minimizing staffing requirements. Operations autonomy has been accomplished in this case, through capitalizing on existing capabilities rather than development of new ground system or flight hardware/software components. Implementation, therefore, was extremely cost effective, with non-recurring expenses limited to engineering labor, and development and test of operational procedures.

Other program's implementation of similar storage techniques would be well suited by ensuring environmental and structural models for simulations, especially flexible-body dynamics models, are well refined and validated prior to simulation execution. This will yield more rapid evaluations of spin dynamics in storage, and allow for fewer modeling runs with higher confidence factor. Early, high fidelity analysis of fuel slosh and Moments Of Inertia (MOI) would provide greater confidence in initial spin thruster firing sequences and tighter initial coning angles on-orbit. Execution of a spin in transfer orbit to derive/validate MOI proved invaluable, and should be executed regardless of analyses' fidelity. Integrated thermal models (spacecraft-instrument) were invaluable tools for uncovering unacceptable instrument thermal conditions that were rectified by heater additions. However, with the tight time constraints for ZAP development resulting in final thermal results late in the study, this parallelism to GOES-10 production caused significant redesign and reharnessing of an assembled observatory to incorporate heater modifications. Defining heater requirements, implementing fixes in advance of system integration, and testing in thermal vacuum chambers would greatly reduce the uncertainties and overall cost of heater implementation.

Further refinements and automation in ZAP operations are currently under investigation. Addition of a flight-proven expert system, Generic Spacecraft Analyst Assistant (GenSAA) is being evaluated for near-term incorporation. This system is already in limited use on the NOAA-K spacecraft, operated form the same NOAA Control Center as GOES. The system will continuously monitor spacecraft system's health and alert NOAA crews if changes in state or telemetry limit violations occur, will provide automated assistance in stepping through contingency flow charts, allow engineers to develop rule-based contingency procedures, will automatically execute daily non-operational commanding to verify links, will provide recall and automatic paging of off-line engineers, and may eventually enable engineers to monitor spacecraft telemetry from many off-site locations. This automation will provide the flexibility and ease of operations monitoring to allow integration of a fourth spacecraft (second in storage) on-orbit without increasing staffing or dedicated ground system resources.

With the development and adoption of on-orbit storage, the GOES Program has accomplished a sea-change in on-orbit asset allocation and launch policy. The ability to maintain one or more spacecraft on-orbit as a mission spare(s) without compromise to their 5 year mission-life, is a dramatic move forward in providing continuous weather data for the NWS. Guaranteed replacement of an operational observatory's failure within 45 days, means virtually uninterrupted weather monitoring and storm watch capabilities are available to preserve life and property across the United States.